

Service Life Extension of the Propulsion System of Long-Term Manned Orbital Stations

Ulhas Kamath*

The Boeing Company, Houston, TX 77059

Sergei Kuznetsov†

Khrunichev Space Center, Moscow 107996

and

Victor Spencer‡

NASA Lyndon B. Johnson Space Center, Houston, TX 77058

One of the critical non-replaceable systems of a long-term manned orbital station is the propulsion system. Since the propulsion system operates beginning with the launch of station elements into orbit, its service life determines the service life of the station overall.

Weighing almost a million pounds, the International Space Station (ISS) is about four times as large as the Russian space station Mir and about five times as large as the U.S. Skylab. Constructed over a span of more than a decade with the help of over 100 space flights, elements and modules of the ISS provide more research space than any spacecraft ever built. Originally envisaged for a service life of fifteen years, this Earth orbiting laboratory has been in orbit since 1998. Some elements that have been launched later in the assembly sequence were not yet built when the first elements were placed in orbit. Hence, some of the early modules that were launched at the inception of the program were already nearing the end of their design life when the ISS was finally ready and operational. To maximize the return on global investments on ISS, it is essential for the valuable research on ISS to continue as long as the station can be sustained safely in orbit. This paper describes the work performed to extend the service life of the ISS propulsion system.

A system comprises of many components with varying failure rates. Reliability of a system is the probability that it will perform its intended function under encountered operating conditions, for a specified period of time. As we are interested in finding out how reliable a system would be in the future, reliability expressed as a function of time provides valuable insight.

In a hypothetical bathtub shaped failure rate curve, the failure rate, defined as the number of failures per unit time that a currently healthy component will suffer in a given future time interval, decreases during infant-mortality period, stays nearly constant during the service life and increases at the end when the design service life ends and wear-out phase begins.

However, the component failure rates do not remain constant over the entire cycle life. The failure rate depends on various factors such as design complexity, current age of the component, operating conditions, severity of environmental stress factors, etc. Development, qualification and acceptance test processes provide rigorous screening of components to weed out imperfections that might otherwise cause infant mortality failures.

If sufficient samples are tested to failure, the failure time versus failure quantity can be analyzed statistically to develop a failure probability distribution function (PDF), a statistical model of the probability of failure versus time. Driven by cost and schedule constraints however, spacecraft components are generally not tested in large numbers. Uncertainties in failure rate and remaining life estimates increase when fewer units are tested. To account for this, spacecraft operators prefer to limit useful operations to a period shorter than the maximum demonstrated service life of the weakest component.

Running each component to its failure to determine the maximum possible service life of a system can become overly expensive and impractical. Spacecraft operators therefore, specify the required service life and an acceptable factor of safety (FOS). The designers use these requirements to limit the life test duration. Midway through the design life, when benefits justify additional investments, supplementary life test may be performed to demonstrate the capability to safely extend the service life of the system.

* Senior Technical Lead, Propulsion Division, Boeing Defense, Space & Security, MC HB5-30

† Division K02 Chief, Khrunichev State Research & Production Space Center

‡ ISS Propulsion System Manager, Propulsion and Power Division, EP4. AIAA Member

An innovative approach is required to evaluate the entire system, without having to go through an elaborate test program of propulsion system elements. Evaluating every component through a brute force test program would be a cost prohibitive and time consuming endeavor. ISS propulsion system components were designed and built decades ago. There are no representative ground test articles for some of the components. A 'test everything' approach would require manufacturing new test articles. The paper outlines some of the techniques used for selective testing, by way of cherry picking candidate components based on failure mode effects analysis, system level impacts, hazard analysis, etc.

The type of testing required for extending the service life depends on the design and criticality of the component, failure modes and failure mechanisms, life cycle margin provided by the original certification, operational and environmental stresses encountered, etc. When specific failure mechanism being considered and the underlying relationship of that mode to the stresses provided in the test can be correlated by supporting analysis, time and effort required for conducting life extension testing can be significantly reduced.

Exposure to corrosive propellants over long periods of time, for instance, lead to specific failure mechanisms in several components used in the propulsion system. Using Arrhenius model, which is tied to chemically dependent failure mechanisms such as corrosion or chemical reactions, it is possible to subject carefully selected test articles to accelerated life test. Arrhenius model reflects the proportional relationship between time to failure of a component and the exponential of the inverse of absolute temperature acting on the component.

The acceleration factor is used to perform tests at higher stresses that allow direct correlation between the times to failure at a high test temperature to the temperatures to be expected in actual use. As long as the temperatures are such that new failure mechanisms are not introduced, this becomes a very useful method for testing to failure a relatively small sample of items for a much shorter amount of time.

In this article, based on the example of the propulsion system of the first ISS module Zarya, theoretical approaches and practical activities of extending the service life of the propulsion system are reviewed with the goal of determining the maximum duration of its safe operation.



Service Life Extension of the ISS Propulsion System

Ulhas Kamath

The Boeing Company
13100 Space Center Blvd
Houston, TX 77059-3556
281-226-6441

ulhas.p.kamath@boeing.com

Gregory Grant

The Boeing Company
13100 Space Center Blvd
Houston, TX 77059-3556
281-226-6321

gregory.e.grant@boeing.com

Sergei Kuznetsov

Khrunichev Space Center
Moscow 107996

adm_211@bk.ru

Sergey Shaevich

Khrunichev Space Center
Moscow 107996

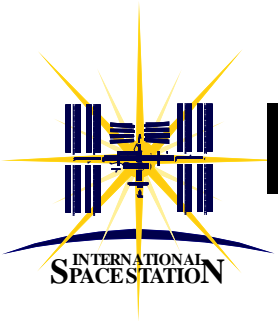
ShaevichS@Khrunichev.com

Victor Spencer

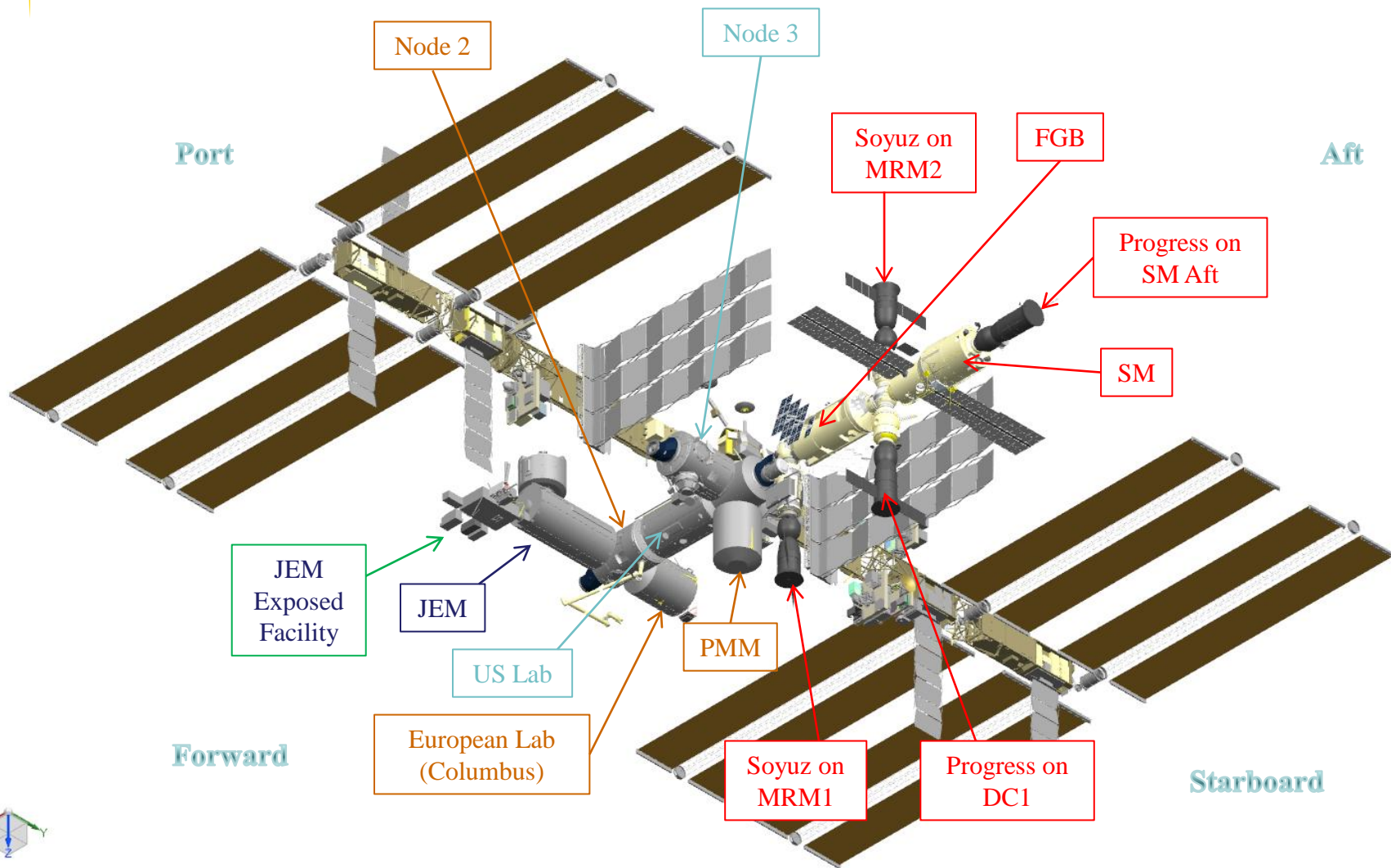
NASA Johnson Space Center, EP4
Houston, TX 77058
281-483-6438

victor.spencer-1@nasa.gov





International Space Station



Functional Cargo Block

- First ISS Element
- Known by its Russian acronym FGB
- U.S. owned Russian Module
- Used primarily for cargo and propellant storage

Length	12.99 m
Maximum diameter	4.1 m
Mass	24,968 kg
Pressurized volume	71.5 m ³
Solar array span	24.4 m
Array surface area	28 m ²
Power supply (avg.)	3 kW
Propellant mass	3,800 kg
Launch date	20-Nov-98



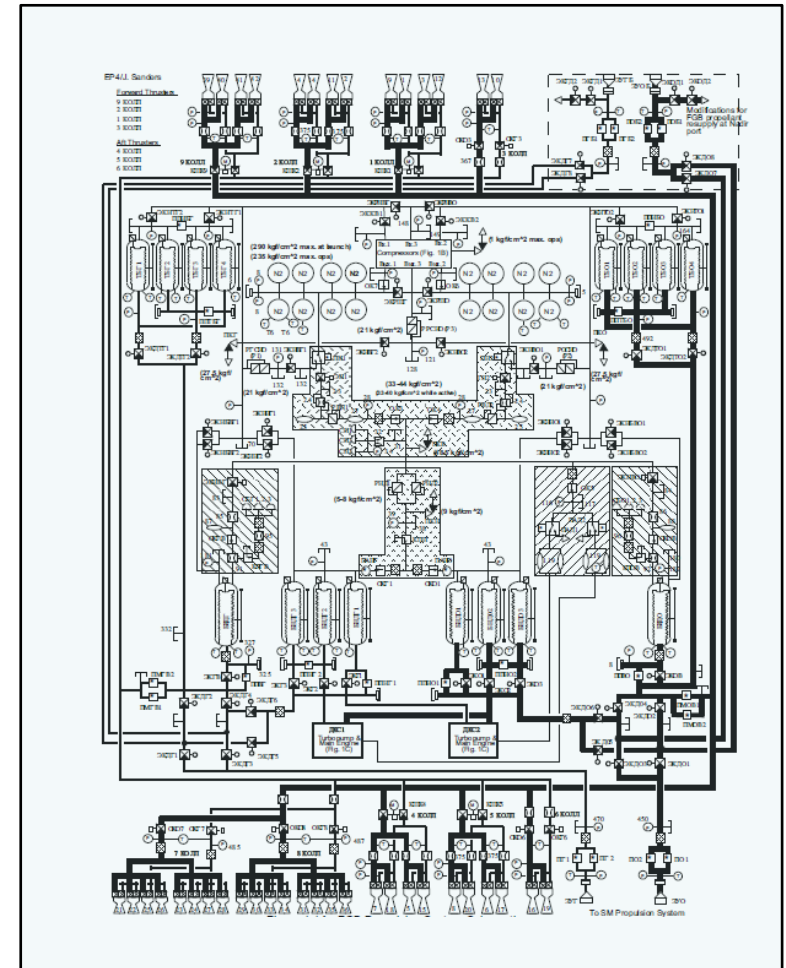
- Two docking interfaces that support propellant transfer



FGB Propulsion System

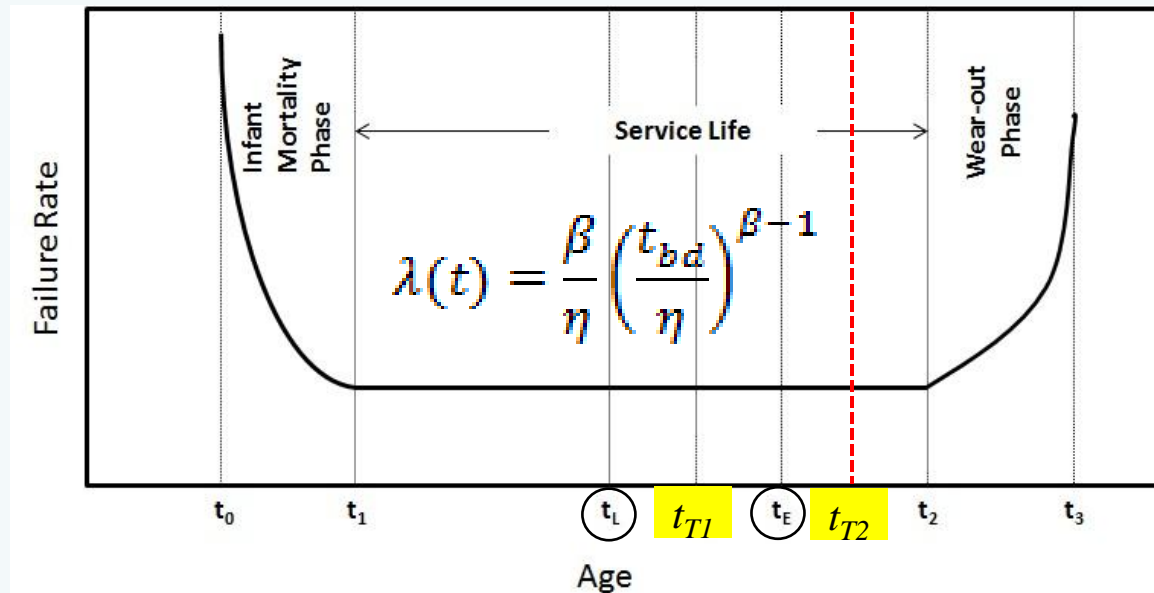


- Stores ~6 MT propellants
- Feeds SM/Progress thrusters
- Refueled by Progress/ATV
- Over 200 components:
 - 16 propellant tanks,
 - 16 pressurant tanks,
 - 42 thrusters,
 - 3 compressors,
 - 14 check valves,
 - 9 safety relief valves,
 - 32 pyrotechnic valves,
 - 7 pressure regulators, and
 - Over 70 isolation valves.



Service Life Extension

Hypothetical Bath Tub Curve



- Failure rate as a function of time:
 - Decreases with time when $\beta < 1$
 - Increases with time when $\beta > 1$
 - Constant failure rate when $\beta = 1$

t_{bd} = time to break down;
 β and η are shape and scale factors of Weibull PDF

- Additional testing to t_{T2} allows extension from initial certified life, t_L to t_E
- Factor of Safety (FOS) remains unchanged

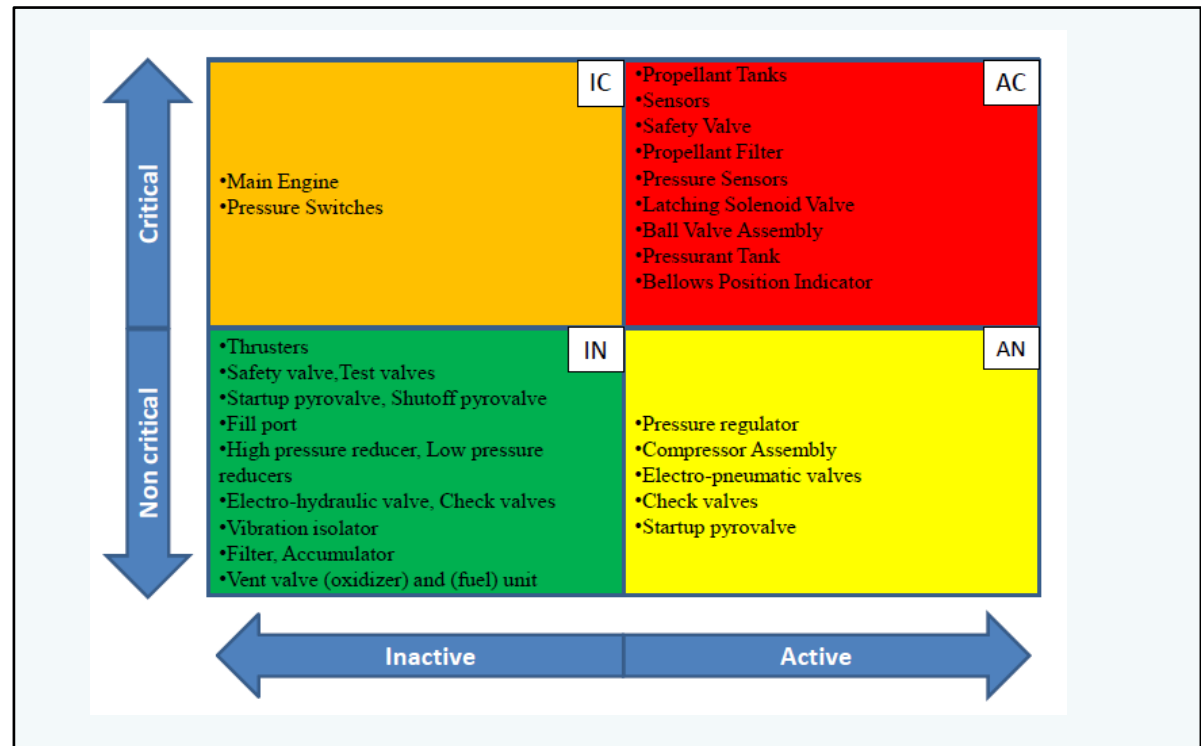
$$FOS = \frac{(t_{T1} - t_1)}{(t_L - t_1)} = \frac{(t_{T2} - t_1)}{(t_E - t_1)}$$



Optimization



- Selection based on failure modes and criticality
 - Systems used for propellant storage/transfer
 - Systems isolated but critical
 - Less critical active systems
- Hazard analysis
- Redundant systems
- Fault tolerance



Arrhenius Model

$$\alpha = \frac{t_T}{t_L} \propto e^{\left[\frac{1}{T_T} - \frac{1}{T_L}\right]}$$

α = Acceleration Factor

t_T = Test Duration

t_L = Component Life

T_T = Average Temperature during Test

T_L = Average Temperature during Ops

- Components with demonstrated cycle life margin
- Single test for multiple units on the fleet leader
- Accelerated Life Test (ALT)
 - Selected materials, parts and soft goods
 - Arrhenius model simulates corrosion with propellant exposure

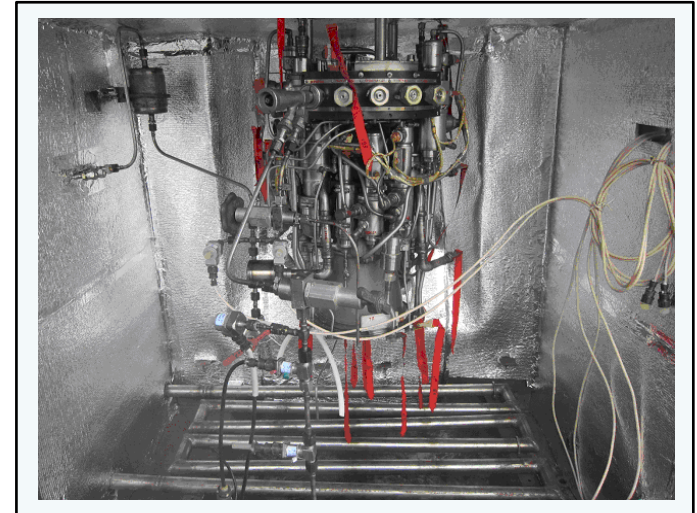
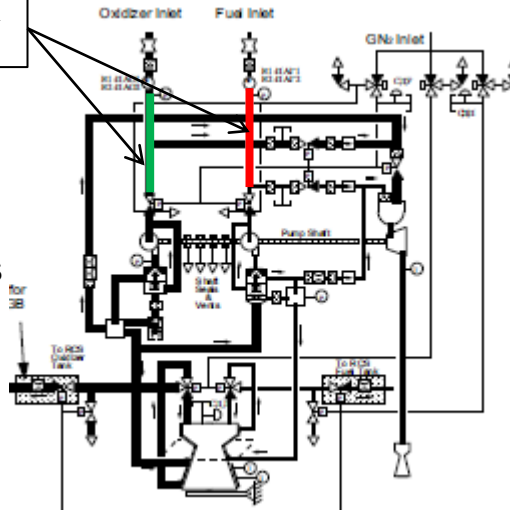


Main Engine

Line segments with
trapped propellants

- Structural/leakage integrity

- Engines were isolated 2 years after FGB was launched.
- Trapped propellants pose corrosion concern.



- Accelerated Life Test (ALT) of Main Engine

- Inlet line filled with 3.5 liter of N_2O_4 at 0.3 MPa and 323 K
- ALT duration = 225 days
- Passed leakage integrity and defect analysis
- Unit cleared for FGB service life until 2028.



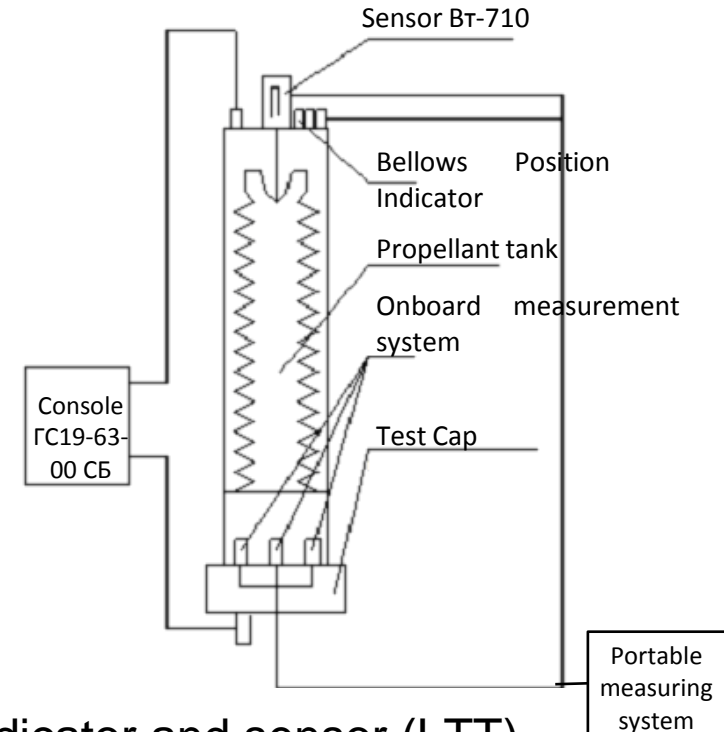


Propellant Tank

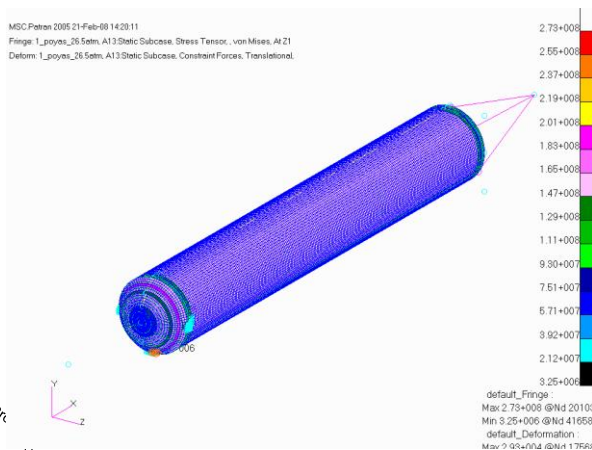


- Bellows cycle life
 - Demonstrated 111 cycles on multiple tanks

Start of Operating Period	End of Operating Period	Number of Years	Expected Cycles per year	Expected Cycles over period	Safety Factor	Test Cycles Applied
1998	2013	15	2	30	1.5	45
2013	2020	7	4	28	1.5	42
2020	2028	8	2	16	1.5	24
Cumulative		30		74	1.5	111



- Structural integrity verified by FEM
 - Al-Mg3 shell, stainless steel bellows

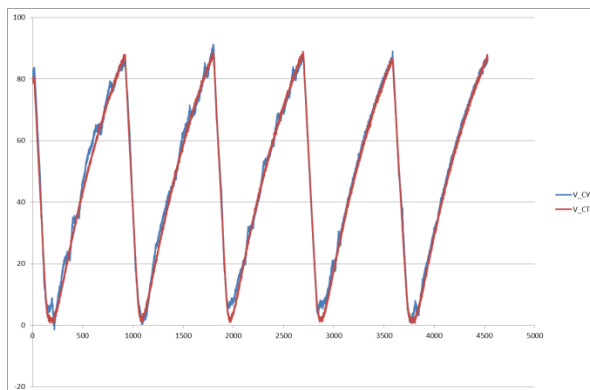


- Bellows position indicator and sensor (LTT)
 - Accelerated aging with propellant exposure
 - Mounted in test chambers filled with 50 mg/m³ propellant vapor concentration at 0.11 MPa and 323 K
 - LTT failed when exposed to worst case N₂O₄ concentration beyond 26 years (ALT)
 - Risk accepted by NASA due to low probability failure mode.



D-Unit Testing

- Simultaneous testing of multiple components
 - 32 cycles on pressure sensor, pressure indicator, GN₂ tank, safety valve, solenoid valve and the ball valve.
- De-mineralized water transferred between two propellant tanks
 - Simulated propellant transfer to/from the FGB tanks
 - Accumulated 111 bellows cycles
 - Forward/reverse flow across propellant filter
- Accelerated aging of multiple components
 - Ball valve, filter, safety valve...
 - Nominal results after ALT and defect analysis

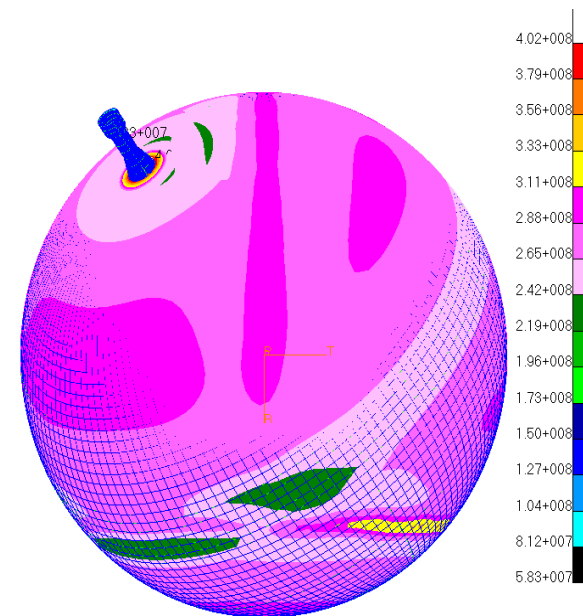




Pressurant Tank

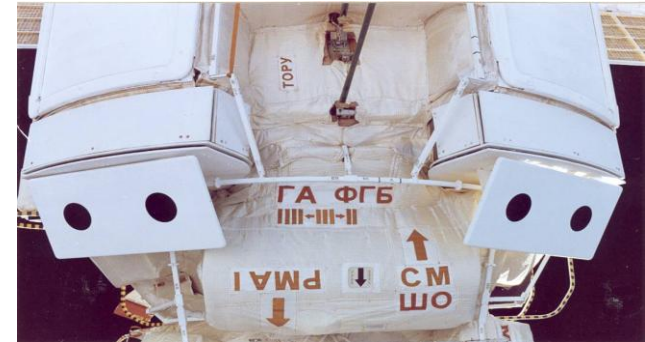


- FGB has 16 high pressure GN₂ storage tanks arranged in 2 functionally redundant sections
- Classified as Active -Critical (AC) component based on SLE optimization
- 32 pressure cycles added on the D-Unit GN₂ tanks
- FEM performed to assess structural integrity at high pressure.
- Results support plans to extend life until 2028.



Compressor Assembly

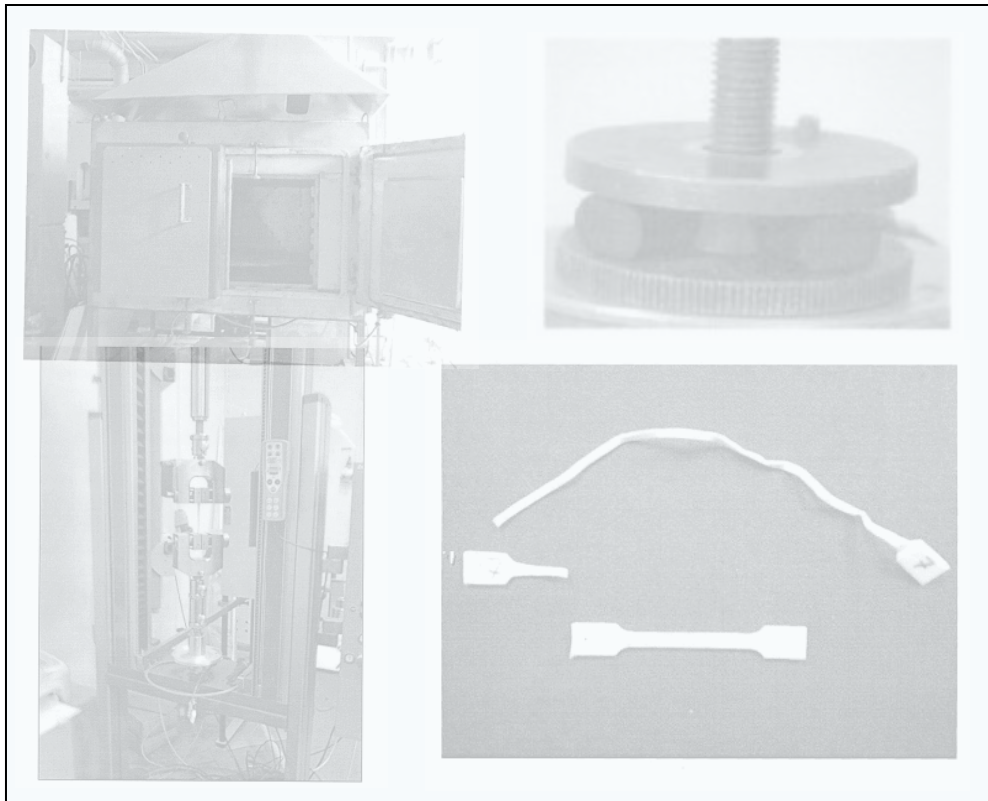
- FGB has 3 functionally redundant compressors housed in a pressure tight nitrogen chamber.
- Classified as Active but Non-Critical (AN) component based on SLE optimization



- Ground test unit was used to simulate flight like operations
- Original certification covers cycle life until 2028
- Heat exchanger materials assessed for long term exposure to Triol coolant.
- Soft goods test provides basis for extending service lives of components within the compressor assembly
 - Pressure reducer, check valve, safety valve, electro-pneumatic valve,...

Soft Goods

- Accelerated aging of representative coupons from multiple components
- Seals and O-rings in deformed and non-deformed state
- Test conditions derived from proprietary statistical and probabilistic models
- Thermal chamber for heating coupons to 343 K for 30 days.
- Pressure tight containers for high pressure application.
- Hydraulic press to measure strain and strength properties.
- Contact stress relaxation determined using axial compression relaxation instrument



Results provide basis for extending service life until 2028.



Summary



- The FGB is the first element of the ISS, built in Russia under a U.S. contract.
- Original certification for FGB operations expired in 2013.
- Efforts to extend the FGB service life until 2028 are discussed.
- Project adopted methods to
 - Identify the life limiting components
 - Optimize the SLE efforts based on hazard analysis, failure modes/criticality analysis and validation requirements
 - Devise and execute a comprehensive, multipronged test and analysis campaign
 - Integrate the results and provide expert assessment
- Results provide the basis for extending the service life of FGB propulsion system until 2028.



Authors



ULHAS KAMATH is a Senior Technical Lead at Boeing-Houston, responsible for Systems Integration of the International Space Station Propulsion Systems and is involved in the formulation and development of architectures for Human Space Exploration beyond Low Earth Orbit. Prior to ISS, he supervised the design, development, testing, analysis and operations of communications satellites at Intelsat of Washington, DC and the Indian Space Research Organization. He holds a bachelor's degree in Mechanical Engineering from University of Mysore, a Ph.D. in Aerospace Engineering from Indian Institute of Science, and an MBA from University of Houston-Clear Lake.



GREGORY GRANT is the FGB Service Life Extension Project Manager for the International Space Station. The project scope encompasses the extension of operational service life of the FGB module non-replaceable subsystems and structural elements, as well as developing diagnostics methods for predicting failures and providing spare subsystem components. Prior to this work he was involved in supervising the production, testing, and on-orbit checkouts of the FGB module. He holds a bachelor's degree in Aerospace Engineering from the Texas A&M University.



SERGEI KUZNETSOV is a Head of department responsible for development, testing and exploitation of spacecrafts and launchers propulsion and thermal control systems at Khrunichev Space Center. Participated in works on the FGB propulsion and thermal control systems life extension until 2028. Being at different positions, participated in new developments of propulsion and thermal control systems in the frames of both Khrunichev and foreign customers projects. In 2000 graduated from Moscow Aviation Technology University and received a specialization "aviation engines and power systems".





Authors



SERGEY SHAEVICH is the ISS Program Director at Khrunichev Space Center since 1994 until now. Being at different positions, from designer to head of design and development department, participated in development and creation of manned long-term stations “Salyut”, heavy transport vehicles “Kosmos” and modules of “Mir” station and in development and creation of the ISS first element FGB “Zarya” as the ISS Program Director. In 2014 managed a work on the FGB Life extension until 2028 with regard to non-replaceable equipment. In 1968 graduated from Bauman Moscow Technical University and received a degree “mechanical engineering”. In 2000 defended his Ph.D. Degree in the area of space hardware design and development. Dr. Shaeovich is an author of 28 published works and more than 30 patents in the area of rockets and space science.



VICTOR SPENCER is the Propulsion System Manager for the International Space Station for NASA and is also working with commercial partners to design and develop the next generation of human launch vehicles. Prior to working on the ISS project, he was involved in working on the maintenance and design of new propulsion upgrade hardware for the Space Shuttles, and prior to that, the concept and design of both lunar and Mars human landing and ascent propulsion systems. In addition to his 22 years in the Propulsion Division at Johnson Space Center, he has also done work tours in both the Safety and Mission Assurance and the Manufacturing and Design Divisions at NASA. Mr. Spencer holds a bachelor's degree in Aerospace Engineering from the Wichita State University.